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THE BOX-BEAM BURSTER ENERGY ABSORBING TUBE - BRIDGE PIER (BEAT-BP) PROTECTION SYSTEM

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ABSTRACT

A new box-beam Burster Energy Absorbing Tube Bridge Pier (BEAT-BP) protection system was successfully crash tested according to the safety performance criteria presented in NCHRP Report No. 350. The system is comprised of two BEAT energy absorbing crash cushions and a frame that envelops the bridge piers. Because of the close proximity to the piers, the system has a significantly smaller footprint that other available options. Three crash tests were considered necessary to evaluate the BEAT-BP system and were conducted successfully: pickup truck CIP transition test at bridge pier (test designation 3-21), pickup truck CIP test at connection between crash cushion and tubular frame structure (test designation 3-38), and pickup truck end-on test for the crash cushion (test designation 3-31). A total of four crash tests were conducted, including one failed test (test no. BP-2). The BEAT-BP protection system performed satisfactorily in all three required crash tests, meeting all evaluation criteria set forth in NCHRP Report 350 guidelines.

INTRODUCTION

The box-beam Burster Energy Absorbing Tube Bridge Pier protection system, herein referred to as BEAT-BP, is based on the bursting tube technology utilized in the box-beam burster energy absorbing terminal (BEAT)[1-2] and single-sided crash cushion (BEAT-SSCC)[3]. The first design objective was to minimize both the longitudinal and lateral extent of the barrier in regard to the bridge piers. In typical median applications, this reduction in extent greatly reduces the soil grading necessary for installation, as well as the concerns for maintenance within the envelope of the system. The second design objective was to reduce the complexity and cost from other NCHRP 350 compliant pier protection alternatives.

BEAT-BP PROTECTION SYSTEM

The BEAT-BP protection system, as shown in Figure 1, consists of two BEAT energy absorbing crash cushions combined with a tubular structure around the bridge piers. The crash cushions provide protection for end-on impacts while the tubular structure shields the bridge piers from side impacts by errant vehicles. The tubular structure around the bridge piers is modular in nature and can be adjusted to accommodate different number, size, and spacing of bridge piers. The crash cushions are designed with two stages of energy absorption and sufficient capacity to absorb the kinetic energy of a 2000-kg (4,409-lb) pickup truck impacting at a nominal speed of 100 km/h (62.2 mph). Note that the length of the stage 2 energy absorbing tube may be lengthened to increase the capacity of the crash cushion to handle higher energy impacts.

The crash cushions perform similarly to other BEAT terminals and crash cushions. When the crash cushion is impacted end-on by an errant vehicle, the impact head will engage and interlock mechanically with the front of the vehicle. As the vehicle proceeds forward, the impact head will be pushed forward along the box-beam rail element. The impact head will then contact the post breaker beam and break off the first (end) steel breakaway post, thus releasing the cable anchorage.

Shortly after breaking of the first (end) post, the tapered mandrel will contact the end of the stage 1 energy absorbing tube and be forced inside the tube. Cracks will then be initiated at the corners of the tube, these crack locations are controlled by notches cut into the end of the tube. As the vehicle proceeds forward pushing the impact head into the tube, the cracks will continue to propagate in front of the impact head until:

1) The vehicle comes to a controlled and safe stop;
2) The vehicle safely yaws away and loses contact with the tube/terminal; or
3) The entire length of the stage 1 energy absorbing tube is used up.

Upon complete bursting of the stage 1 energy absorbing tube, the process will repeat with the stage 2 energy absorbing tube until:

1) The vehicle comes to a controlled and safe stop;
2) The vehicle safely yaws away and loses contact with the tube/terminal; or
3) The stage 2 energy absorbing tube is used up. Note that the bursting

process could proceed beyond the end of the stage 2 energy absorbing tube, but the force level will likely to be higher in the connection area between the crash cushion and the tubular frame.

For impacts that are end-on at an angle, bursting of the tubular rail element will proceed until the vehicle yaws out and/or buckles the rail element and gates behind the crash cushion. Similarly, for impacts near the end of the crash cushion (e.g., between posts 1 and 2), the impacting vehicle will break off the end post, buckle the rail element, and gate behind the crash cushion.

For impacts into the side of the crash cushion, downstream of the beginning of length-of-need (which is selected to be post 3 or 2.9 m (9 ft 6 in.) from the end of the crash cushion) the crash cushion will contain and redirect the impacting vehicle. The cable attachment will provide the necessary anchorage to resist the tensile forces acting on the rail element to contain and redirect the vehicle.

For impacts into the side of the tubular frame shielding the bridge piers, the tubular frame will contain and redirect the impacting vehicle. The anchorage systems for the crash cushions will also provide the necessary anchorage for the tubular frame. In addition, the tubular frame is stiffened by the double rail and reduced post spacing around bridge piers and diagonal and cross struts.

BEAT-BP Crash Cushion

The BEAT-BP crash cushion, Figure 2, is approximately 7.9 m (26 ft) in length from the nose of the impact head to the end of the Stage 2 energy absorbing tube (or where the crash cushion connects to the tubular frame for the bridge piers). The major components of the crash cushion are as follows:

A. An impact head assembly,
B. A 2438 mm (8 ft) long section of 152 x 152 x 3.2 mm (6 x 6 x 1/8 in.) box-beam rail for the stage 1 energy absorber,
C. A 4940 mm (16 ft 2-1/2 in.) long section of 152 mm x 152 mm x 4.8 mm (6 in. x 6 in. x 3/16 in.) box-beam rail for the stage 2 energy absorber,
D. A steel breakaway end post,
E. Steel breakaway posts for posts 2 through 6,
F. A cable anchorage system,
G. A post-breaker attached to the end post, and
H. A restraining cable.

BEAT-BP Tubular Frame

Shielding for the bridge piers is provided by a tubular frame as shown in Figure 2. The tubular frame is modular in nature, i.e., the design will handle any number, size, and spacing of bridge piers. The major components of the tubular frame are as follows:

1. Double rail section at bridge pier,
2. Cross strut,
3. Connecting rail section,

4. Angled end strut,
5. Connection with crash cushion.

The tubular frame forms an envelope around the bridge piers. For each bridge pier, there is a double rail section on each side, putting the face of the rail at least 305 mm (12 in.) away from the pier. The double rail sections are joined by connecting rail sections to form a continuous rail in front the bridge piers. The two rails are then joined by angled struts on both ends to form a parallelogram. The end struts are angled so that errant vehicles that go behind the crash cushion would not impact the end strut at a right angle. Instead, the angled strut would redirect the vehicle away from the bridge piers. In addition, there is a cross strut at each bridge pier to stiffen the frame and to generate composite action from the rails on both sides.

A double rail section is placed in front of each bridge pier. The front rail section is 4858 mm (15 ft 11-1/4 in.) long and the back rail section is 2654 mm (8 ft 8-1/2 in.) long. Both rail sections are fabricated from TS 152 x 152 x 4.8 mm (6 x 6 x 3/16 in.) structural tubing. The two rail sections are skip welded together with the downstream ends offset by a distance of 270 mm (10-5/8 in.). In instances where the longitudinal length of the pier exceeds the length of this section, placement relative to the upstream edge of the pier is maintained, and a second blockout section would be utilized on the downstream edge of the pier. The annulus between the two section would be filled with an additional section fabricated from TS 152 x 152 x 4.8 mm (6 x 6 x 3/16 in.) structural tubing. Posts would not be utilized on the face of the pier.

The two double rail sections on the sides of the bridge pier are connected with a cross strut. The strut is 1219 mm (4 ft) long and fabricated from TS 152 x 152 x 4.8 mm (6 x 6x 3/16 in.) structural tubing. Splice plates are welded to the top and bottom on both ends of the strut for bolting to the back rail section. These cross struts can either be located internally or externally in relation to the piers.

The double rail sections at the bridge piers are joined with connecting rail sections, also fabricated from TS 152 x 152 x 4.8 mm (6 x 6x 3/16 in.) structural tubing. The length of the connecting rail sections may vary, depending on the spacing between the bridge piers. Standard box-beam rail splice plates are used to join the rail sections. Each connecting rail section has one or more supporting posts. These posts are standard 1829 mm (6 ft) W152x13.4 (W6 x 9) guardrail line posts. The same special support brackets with box-rail rail blockouts are used for attaching the rail to the posts. The post spacing for the posts in the connecting rail section is 1219 mm (4 ft).

The two rails are joined by angled struts on both ends to form a parallelogram. As mentioned previously, the end struts are angled so that errant vehicles that go behind the crash cushion would not impact the end strut at a right angle, but would be redirected. The angle is selected to be 34 degrees. The angled strut is connected to the back rail with a special bent splice, which is fabricated from welding two short sections of TS 127 x 127 x 4.8 mm (5 x 5 x 3/16 in.) structural tubing together. The angled strut is attached to the front rail section and the stage 2 energy absorbing tube of the crash cushion with a Y connection.

The Y connection consists of a 292 mm (11-1/2 in.) long, TS 152 x 152 x 4.8 mm (6 x 6 x 3/16 in.) center tube. Two 948 x 102 x 13 mm (37-5/16 x 4 x ½ in.) splice plates are welded to the top and bottom of the center tube. The stage 2 energy absorbing tube from the crash cushion is attached to the upstream end of the splice plates and the double rail section is attached to the downstream end. A TS 114 x 114 x 4.8 mm (4.5 x 4.5 x 3/16 in.) structural tubing is welded to one side of the center tube at an angle of 34 degrees and a length of 357 mm (14 in.) on the short side for bolting of the angled end strut.

As mentioned previously, the tubular structure around the bridge piers is modular in nature and can be adjusted to accommodate different number. size, and spacing of bridge piers. The test setup has two 1219 mm (48 in.) square bridge piers spaced 6096 mm (20 ft) apart. This configuration was selected as being critical for snagging of the impacting vehicle. Round piers or smaller rectangular piers would have significantly lower snagging potential. For bridges with different numbers of piers, each pier will be shielded by the double rail section with the five supporting posts and cross strut. The double rail sections are then joined by connecting rail sections to form a continuous rail. The standard setup will accommodate bridge pier sizes of up to 1219 mm (48 in.) square, which should be adequate for most situations. For larger bridge piers, the structural frame can be customized to accommodate the specific size of the bridge pier. Finally, different spacing between the bridge piers is accommodated by adjusting the length of the connecting rail sections.

SUMMARY OF CRASH TEST RESULTS

Crash Test Matrix

The BEAT-BP system consists of two BEAT energy absorbing crash cushions combined with a tubular frame or structure around the bridge piers. The crash testing requirements for the crash cushions are different from those of the tubular structure. Thus, discussions on the crash test matrix are presented separately for each of these two components.

Crash Cushion Section

According to guidelines presented in *NCHRP Report 350*[4], a total of up to seven (7) crash tests may be required for evaluation of a gating redirective crash cushion under test level 3 (TL-3) conditions. Because the design of the crash cushion section of the BEAT-BP is very similar to those of the box-beam burster energy absorbing guardrail terminal (BEAT) and the single-sided crash cushion (BEAT-SSCC)[1-3] only the pickup truck head-on test (test designation 3-31) was performed to demonstrate the satisfactory impact performance of the crash cushion section of the BEAT-BP. The rationale was that this crash test is the most critical of the seven required tests and, if successful, would demonstrate that the crash cushions would perform satisfactorily in conjunction with the tubular frame structure shielding the bridge piers. This previous testing included a backside/reverse direction impact on the system, demonstrating the systems safety for median applications.

At the connection between the crash cushion and the tubular frame structure, there is a hard point where the end of the crash cushion, the box-beam rail on the front side, and the diagonal rail from the back-side are joined together with a Y-connector. To assure that an impacting vehicle would not pocket or snag at this hard point, it was decided to conduct the pickup truck, critical impact point (CIP) test, sometimes referred to as the “coffin-corner” test (NCHRP Report 350 test designation 3-38), even though it is intended for non-gating devices. This test involves a 2,000-kg (4,409-lb) pickup truck impacting the crash cushion at the critical impact point at a nominal impact speed and angle of 100 km/h and 20 degrees. The CIP is determined with computer simulation to result in maximum deflection of the barrier at the hard point.

Tubular Frame Section

The tubular frame section basically serves the function of a barrier length-of-need section, i.e., shielding errant vehicles from the bridge piers. The major concern is to keep the impacting vehicle from pocketing or snagging at the bridge piers. Thus, it was determined that the worst case scenario was to test the structure as a transition section, i.e., test designation 3-21, which involves a 2,000-kg (4,409-lb) pickup truck impacting the barrier at the critical impact point (CIP) at a nominal impact speed and angle of 100 km/h and 25 degrees. The CIP was determined with computer simulation to result in maximum dynamic deflection at the bridge pier.

Summary

In summary, based on evaluation of previous testing, three crash tests, the pickup truck transition CIP test (test designation 3-21), 3-31, and 3-38, were needed to qualify the BEAT-BP under *NCHRP Report 350* guidelines, these are described as:

1. Test designation 3-21. A 2,000-kg (4,409-lb) pickup truck impacting the tubular frame section barrier at the critical impact point (CIP) at a nominal impact speed and angle of 100 km/h and 25 degrees, respectively. The CIP is determined from computer simulation to result in maximum dynamic deflection at the bridge pier.

2. Test designation 3-31. A 2,000-kg (4,409-lb) pickup truck impacting the crash cushion end-on at a nominal impact speed and angle of 100 km/h (62.2 mph) and 0 degree, respectively, with the centerline of the vehicle aligned with the centerline of the nose (i.e., end post) of the cushion.

3. Test designation 3-38. A 2,000-kg (4,409-lb) pickup truck impacting the crash cushion at the critical impact point at a nominal impact speed and angle of 100 km/h and 20 degrees, respectively. The CIP is determined from computer simulation to result in maximum deflection of the barrier at the hard point.

Summary Of Crash Test Results

A total of four full-scale crash tests were conducted at the Midwest Roadside Safety Facility, including one failed test (test no. BP-2). Table 1 shows a summary of the results of these four crash tests and brief descriptions of these tests are presented as follows. The tests are presented in the same order as they were conducted chronologically.

Test No. BP-1

The first test conducted was the pickup truck transition CIP test (NCHRP Report 350 Test Designation 3-21). The CIP was determined, based on results of BARRIER VII simulation runs, to be 152-mm (6 in.) upstream of post no. 13 so as to produce the maximum dynamic deflection at the downstream bridge pier. The vehicle impacted the crash cushion at a speed and angle of 98.6 km/h (61.3 mph) and 25.3 degrees. Pre-test and post-test photos are shown in Figure 3.

Upon impact, the left-front corner of the pickup truck deformed inward and vehicle began to be redirected by the box beam rail. As the rail deformed the front-left fender of the vehicle inward, the hood and part of the fender protruded over the rail. The left front wheel slid underneath the box beam rail and snagged on post 15, causing the post to bend towards and impact post 16. The left-front corner of the hood that extended over the rail impacted the downstream bridge pier causing the hood to deform and be pushed back towards the windshield. The left front fender also snagged on the bridge pier and deformed backwards. The vehicle continued to redirect and eventually lost contact with the system 4.19 m (13 ft 9 in.) downstream of the impact point. The vehicle veered to the left after leaving the system and came to rest 39 m (128 ft) downstream and 6.2 m (20 ft) to the left of the impact point.

Damage to the test installation was moderate, including the posts, the box-beam rail, and the downstream bridge pier. Post 15 was bent and twisted over at the ground line due to snagging by the left-front wheel. Post 16 was also bent downstream. Damage to the box-beam rail was limited to a slight bend between posts 14 and 15 and contact marks. Minor cosmetic damage was also observed on the downstream bridge pier. The maximum dynamic deflection of the system was measured to be 52-mm (2 in.).

Vehicle damage was extensive, including the left front corner and fender of the vehicle, and driver's side door. The hood was buckled upward and pushed back towards the windshield, which was deformed and cracked. The left-front wheel was pushed inward and back to the firewall causing damage to the suspension. There was significant damage to the occupant compartment, including a large tear of the seam on the front of the floor pan underneath the brake pedal and deformations to the floor pan and the dash. The maximum deflection was measured to be 191 mm (7.5 in.) laterally and 178 mm (7 in.) vertically. The occupant risk factors are well within limits set forth in NCHRP Report 350 guidelines.

This test was judged to be a marginal pass according to evaluation criteria set forth in NCHRP Report 350. The test article contained and redirected the impacting vehicle and the vehicle did not penetrate, underride, nor override the barrier. There were minimal detached elements and debris. The vehicle remained upright during and after the collision. The vehicle's trajectory did not intrude into adjacent traffic lanes. The occupant impact velocities and ridedown accelerations were within the suggested limits imposed by NCHRP Report 350.

However, several concerns were raised during analysis of the test results that rendered the test a marginal pass:

1. Minor windshield cracking due to snagging of the hood and front-left fender on the bridge pier was observed.
2. Occupant compartment deformations observed in the test were as large as 191 mm (7.5 in.) laterally and 178 mm (7 in.) vertically. FHWA has recommended that occupant compartment deformations of more than 150 mm (6 in.).

In an effort to improve the impact performance, a C150 x 12.2 (C6 x 2) channel rubrail was added at a mounting height of 330-mm (13 in.). It was thought the addition of the rubrail would help to reduce snagging of the wheels of the impacting vehicle on the steel posts and the bridge pier as well as to reduce the intrusion of the front-left corner of the vehicle over the tubular rail.

Test No. BP-2

This test is a repeat of test no. BP-1, i.e., pickup truck transition CIP test (NCHRP Report 350 Test Designation 3-21), with the added channel rubrail. The point of impact was again selected to be 152-mm (6 in.) upstream of post 13 so as to produce the maximum dynamic deflection at the downstream bridge pier. The vehicle impacted the crash cushion at a speed and angle of 100.5 km/h (62.5 mph) and 23.7 degrees. Pre-test and post-test photos are shown in Figure 4.

Upon impact, the left-front corner of the pickup truck deformed inward and the vehicle began to be redirected by the box beam rail. As the rail deformed the front-left fender of the truck inward, the hood and part of the fender protruded over the rail. The left front wheel pushed up against the channel rubrail and the tubular frame of the crash cushion began to deflect inward. The left-front corner of the hood that extended over the rail impacted the downstream bridge pier causing the hood to deform and be pushed back towards the windshield. The left front fender of the pickup truck also snagged on the bridge pier and deformed backwards as well. However, there was little or no snagging of the front-left wheel on the posts or the bridge pier due to the channel rubrail. The pickup truck continued to redirect and eventually lost contact with the system 4.19 m (13 ft 9 in.) downstream of the impact point. The vehicle veered to the left after leaving the rail and came to a stop 41 m (135 ft) downstream and 4.8 m (16 ft) to the left of the impact point.

Damage to the test installation was moderate, including the posts, the box-beam rail, the channel rubrail, and the downstream bridge pier. Posts 12 through 14 displayed minor lateral deflections in the soil while posts 15 and 16 were twisted counterclockwise in the soil. Damage to the box-beam rail and the channel rubrail was limited to slight bends in the rail and contact marks along the rail. Minor cosmetic damage was also observed to the downstream bridge pier. The maximum dynamic deflection of the system was measured to be 141 mm (5.6 in.).

Vehicle damage was extensive, including the left front corner and fender of the vehicle, and driver’s side door. The hood was buckled upward and pushed back towards the windshield, which was deformed and cracked. The left-front wheel was pushed inward and back to the firewall causing deformation of the tie-rods and other suspension components. The left-front tire was deflated.

Significant damage was observed to the occupant compartment of the vehicle, including a large tear of the seam on the front of the floor pan underneath the brake pedal and deformations to the floor pan and the dash. The maximum deflection was measured to be 267 mm (10.5 in.) laterally. The windshield was deformed and fractured due to impact by the hood. The occupant risk factors are within limits set forth in NCHRP Report 350 guidelines.

This test was judged to be unacceptable based on the two following factors:

1. There was significant snagging of the hood and the front-left fender on the bridge pier. The hood was pushed backward into the windshield, resulting in unacceptable damage to the windshield.

2. There was significant occupant compartment deformation of up to 267 mm (10.5 in.) laterally. FHWA has recommended that occupant compartment deformations of more than 150 mm (6 in.) in a location where serious injury can result are cause for judging a test as unacceptable. Therefore, the large occupant compartment deformations observed in this test was judged not acceptable.

In light of the unsatisfactory performance of the modified system, it was decided to revert back to the original design and proceed with the remaining crash tests. While the results of test No. BP-1 are marginal, it represents the worst-case scenario for the intended application of this BEAT-BP system. The maximum size of 1.2 m x 1.2 m (48 in. x 48 in.) square was used for the bridge piers. For situations with smaller or round bridge piers, the potential for the hood and the left front fender of the vehicle to snag on the bridge pier would be greatly reduced. Also, the rail element would be able to deflect more, thus reducing the force level and the concentrated loading on the vehicle, resulting in less occupant compartment deformation.

Test No. BP-3

The third test conducted was the pickup truck CIP test, sometimes referred to as the "coffin-corner" test (NCHRP Report 350 test designation 3-38). Note that the system design reverted back to the original design used in test no. BP-1 without a rub rail since the modified system design used in test no. BP-2 did not perform satisfactorily. The CIP was determined, based on results of BARRIER VII simulation runs, to be at post 4 so as to produce the maximum dynamic deflection at the hard point, i.e., the Y-connector joining the end of the crash cushion, the box-beam rail on the front side, and the diagonal rail from the back side. The vehicle impacted the crash cushion at a speed and angle of 101.4 km/h (63.0 mph) and 20.7 degrees. Pre-test and post-test photos are shown in Figure 5.

Upon impact, the left-front corner of the vehicle was deformed inward and the box-beam rail was deflected back and began to redirect the vehicle. As the rail deformed the front-left fender of the truck inward, the hood and part of the fender protruded over the rail. The left-front wheel of the vehicle slid underneath the box-beam rail, turned to the left, and snagged post 6, causing the tire to deflect and the post to fracture. The vehicle continued to move downstream and smoothly traversed the Y-connector. The left-front wheel of the vehicle then snagged post 7. The vehicle lost contact with the system 5.8 m (19 ft) downstream of the impact point. The vehicle veered to the left after leaving the rail and came rest 45 m (148 ft) downstream and 4.5 m (14.7 ft) to the left of the impact point.

Damage to the test installation was moderate, consisting of damage to the posts and the box-beam rail. Post 6 fractured at ground level due to snagging by the front-left wheel and was deposited 6.7 m (22 ft) downstream and 4.6 m (15 ft) to the left of its original position. Deformation of the box-beam rail was observed from post 4 through 9, and buckling was observed in the rail at post 9. A maximum indentation of 9.5 mm (0.4 in.) was found 610 mm (24 in.) downstream of post 4. The maximum dynamic deflection of the system was measured to be 311 mm (12.2 in.).

Vehicle damage was moderate, including the left front corner and fender of the vehicle, and the driver's side door. Significant damage of the front-left portion of the frame of the pickup truck was observed. The front-left wheel was detached and the suspension was disengaged from the frame. The front-left tire was also deflated. Minor deformations of both the floor pan and the dash of the vehicle were observed. The maximum deflection was 83 mm (3.3 in.) vertically near the middle of the driver's side floor pan. The windshield displayed some minor cracking. The occupant risk factors are well within limits set forth in NCHRP Report 350 guidelines.

This test was judged to be acceptable in accordance with evaluation criteria set forth in NCHRP Report 350. The test article contained and redirected the impacting vehicle and the vehicle did not penetrate, underride, nor override the barrier. There were minimal detached elements and debris. There was no significant deformation or intrusion into the occupant compartment. The vehicle remained upright during and after the collision. The vehicle's trajectory did not intrude into adjacent traffic lanes. The occupant risk factors were within suggested limits set forth in NCHRP Report 350.

Test No. BP-4

The fourth and last test conducted was the pickup truck head-on test (NCHRP Report 350 test designation 3-31). The vehicle impacted the crash cushion at a speed and angle of 102.0 km/h (63.4 mph) and 0.6 degree. Pre-test and post-test photos are shown in Figure 3. During this test, the terminal decelerated the vehicle and brought the vehicle to a safe and controlled stop 6.4 m (21 ft) downstream from the impact point.

The terminal performed as designed. Upon impact, the front of the vehicle engaged and mechanically interlocked with the impact head. As the vehicle proceeded forward, the post breaker broke off the end post and initiated the bursting process with the stage 1 energy absorbing tube. The stage 1 energy absorbing tube was completely bursted and the bursting process continued with the stage 2 energy absorbing tube until the vehicle came to a safe and controlled stop against the impact head past post 5. The occupant risk factors were all well within the recommended limits.

Damage to the BEAT-BP crash cushion was moderate, consisting of damage to the posts and the box-beam rail. Posts 1 through 3 were fractured at ground level and post 4 was bent over, but did not fracture. The total bursted length was 5.96 m (19 ft 7 in.), including all 2.44 m (8 ft) of the stage 1 energy absorbing tube and 3.52 m (11 ft 7 in.) of the stage 2 energy absorbing tube. Bursting of the tubes through splice connecting the two tubes caused strips of metal from the stage 1 tube and parts of the splice joint to be disengaged from the system. The system anchorage remained intact, and there was no significant damage to the impact head assembly.

Vehicle damage was moderate and limited to the frontal area. There were minor deformations in both the floor pan and the dash areas. The maximum deflection was 19 mm (3/4 in.) vertically near the front-left side of the hump in the driver's side floor pan and longitudinally. The occupant risk factors were within limits set forth in NCHRP Report 350.

This test was judged to be acceptable in accordance with evaluation criteria set forth in NCHRP Report 350. The test article safely brought the impacting vehicle to a controlled stop. Detached elements and debris from the test installation did not penetrate nor show potential for penetrating the occupant compartment or present undue hazard to the other traffic, pedestrians, or personnel in the work-zone. There were only minor deformation and intrusion of the occupant compartment. The vehicle remained upright during and after the collision. The vehicle's trajectory did not intrude into adjacent traffic lanes.

SUMMARY AND CONCLUSIONS

A new box-beam Burster Energy Absorbing Tube Bridge Piers (BEAT-BP) protection system was successfully crash tested according to the safety performance criteria presented in NCHRP Report No. 350. Three crash tests were considered necessary to evaluate the BEAT-BP system and were conducted successfully: pickup truck CIP transition test at bridge pier (test designation 3-21), pickup truck CIP test at connection between crash cushion and tubular frame structure (test designation 3-38), and pickup truck end-on test for the crash cushion (test designation 3-31). A total of four crash tests were conducted, including one failed test (test no. BP-2). The BEAT-BP protection system performed satisfactorily in all three required crash tests, meeting all evaluation criteria set forth in NCHRP Report 350 guidelines.

The system, because of its close proximity to the piers, will require significantly less soil grading than other alternatives. For illustration, the BEAT-BP is shown in Figure 7 as an overlay of the bull-nose system recently developed by the MwRSF.[5] Because the system requires fewer posts and is based on standard components utilized in the BEAT and the BEAT-MT, it should also be significantly cheaper to purchase and construct.

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TABLE 1. SUMMARY OF CRASH TEST RESULTS

Test No.	Test Designation and Description	Actual Impact Conditions		Occupant Risk				Assessment
		Speed (km/h)	Angle (Deg.)	OIV (m/s)		RA (g's)		
				Long.	Lat.	Long.	Lat.	
BP-1	Test 3-21 - Pickup truck, transition test on CIP.	98.6 (61.3 mph)	25.3	5.4 (17.9 fps)	7.4 (24.4 fps)	13.0	8.2	**MARGINAL PASS**
BP-2	Test 3-21 - Pickup truck, transition test on CIP.	100.5 (62.5 mph)	23.7	5.7 (18.7 fps)	7.1 (23.3 fps)	11.1	18.8	**FAIL**
BP-3	Test 3-38 - Pickup truck, CIP.	101.4 (63.0 mph)	20.7	4.2 (13.7 fps)	6.1 (19.9 fps)	8.6	10.0	**PASS**
BP-4	Test 3-31 - Pickup truck, head-on.	102.0 (63.4 mph)	0.6	9.5 (31.1 fps)	0.3 (0.9 fps)	10.4	2.0	**PASS**

FIGURE 1: Photo of the Test Installation of BEAT-BP

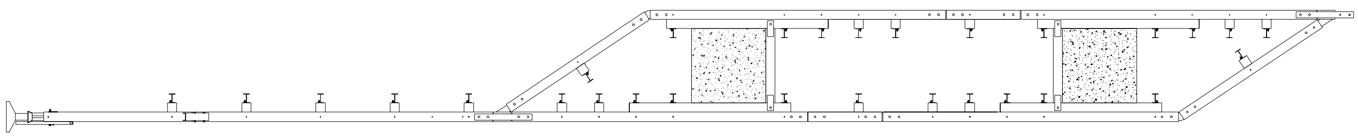

FIGURE 2: Schematic of the BEAT-BP Test Installation (Second Terminal Not Shown)

FIGURE 3: Pre-test and Post-test Photos of BP-1

FIGURE 4: Pre-test and Post-test Photos of BP-2

FIGURE 5: Pre-test and Post-test Photos of BP-3

FIGURE 6: Pre-test and Post-test Photos of BP-4

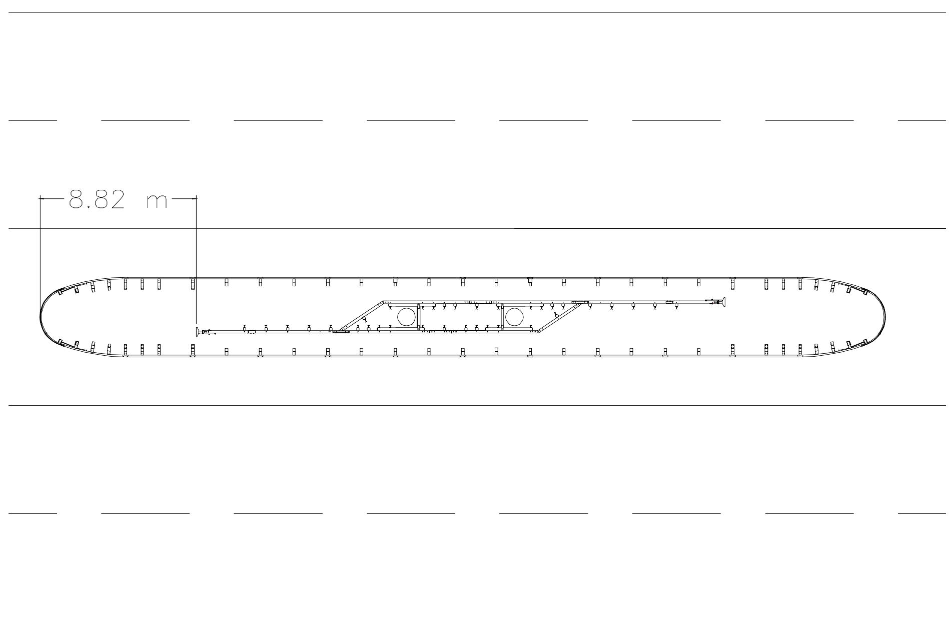

FIGURE 7: Overlay of the BEAT-BP on the NCHRP 350 Compliant Bull-Nose system.